Phase 2 Project Summary

Firm: **CFD Research Corporation**
Contract Number: **NNX10CB66C**
Project Title: **High-Fidelity Gas and Granular Flow Physics Models for Rocket Exhaust Interaction with Lunar Soil**

Identification and Significance of Innovation: Spacecraft rocket exhaust plume induced lunar soil erosion and the consequent dust storm have a severe impact on the exploration habitat. Due to limitations in terrestrial experiments future space exploration programs will require high-fidelity numerical technologies for in-depth analysis of this complex problem. To address this need, the team of CFD Research Corporation (CFDRC) and the University of Florida (UF) has previously developed a unique lunar plume driven erosion simulation toolset with support from a NASA STTR Phase II project by combining soil granular physics simulation modules with CFDRC's Unified Flow Solver (UFS) plume flow simulation modules. This simulation system combines

1. A unified continuum-rarefied flow solver (Unified Flow Solver - UFS) with the ability of simulating plume impingement flow in lunar vacuum environment,
2. Granular solid-fluid interaction models developed by the University of Florida from first principle physics for predicting lunar regolith granular flow behavior,
3. Lagrangian particle transport tools accounting for particle collisions integrated into UFS to simulate dust and debris kinetics and dispersion around the vehicle after liberation.

Technical Objectives and Work Plan: The specific objectives of Phase II research and development effort were the following:

1. Establish irregular particle interaction mechanics models from first principle Lagrangian DEM particle interaction models and formulate accurate constituent models
2. Implement the irregular shaped granular flow mechanics physics models in an Eulerian granular flow model based on particle kinetic formulations
3. Implement the Eulerian granular flow model in multi-phase Eulerian simulation system coupled with the exiting UFS continuum-rarefied flow solver framework
4. Implement turbulence models in the gas phase that account for turbulent Reynolds stresses at the interaction of plume jets with the surface that contribute significantly to crater formation
5. Implement surface roughness effects through turbulence modeling at the gas-surface interface that contribute significantly to viscous erosion effects
6. Perform detailed verification and validation of the integrated simulation tool against experiments with sand, lunar simulants and Martian simulants under earth and reduced gravity conditions
7. Demonstrate the utility and versatility of the newly developed tools to NASA, industry, and the scientific community
8. Transfer the developed granular physics modeling technology to related industry applications for commercialization

Technical Accomplishments: These technology components have been further improved under this Phase II development project. The granular flow constituent physics models are significantly advanced by including the effects of irregular, non-spherical shape of the particles. Traditionally used granular mechanics models are based on mono-disperse spherical particles empiricism unsuitable for capturing the granular mechanics of irregularly shaped grains characteristic of lunar regolith. The granular mechanics constitutive models were developed through innovative Discrete Element Methods simulating non-spherical, jagged particles constructed as clusters of linked/overlapping spheres. This first principle modeling captures the fundamental relationship between particle shape and particle-phase stress, cohesion, and particle flow kinetics.

The granular physics models are implemented in an Eulerian granular flow solver module in the Gerris computational modeling framework that is the foundation of the UFS solver. Implementation of the Eulerian-Eulerian multi-phase solver in the UFS framework required the implementation of a compatible continuum Navier-Stokes gas phase solver module. This development was necessitated by the lack of multi-phase simulation algorithms for gas kinetic solvers such as that implemented in UFS. Simulation of the interaction of the multi-phase gas-granular phases during the fluidization and cratering process is enabled by coupling the gas and granular Eulerian solver modules within the simulation framework.

NASA Application(s): The debris simulation tool will be of first order importance to the Space Exploration program for lunar robotic and human mission architecture definition. The tool will be equally applicable to followon Mars robotic and human missions. The developed technology will also be applicable for analysis of solid propulsion systems with embedded solid particle.

Non-NASA Commercial Application(s): Many potential non- NASA commercial applications exist in civil and military industries. Dust, sand and snow stir-up during helicopter landing and take-off in a desert or arctic environment result in severe visibility impairment (brown-out), windshield abrasion and danger of debris ingestion. Civil engineering and environmental engineering applications include wind-borne landscape erosion and dust transport to populated areas.

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